

Integrating social aspects and group work aspects in engineering design education

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Introduction

Over the last several years, the Institute for Complex Engineered Systems (ICES), from its origins as the Engineering Design Research Center (EDRC), has evolved two elective courses addressing the social and group aspects of engineering design. These courses are offered to students in the engineering undergraduate curricula as part of a design minor. The importance of these courses can be understood in light of the statement in the Report by the National Academy of Engineering on “Engineering as a Social Enterprise” that less than 2% of the population of the United States are engineers (Sladovich, 1991). The social impact of engineers on the day-to-day lives of ordinary people is immense, and creating an awareness of their impact on society has been rather sparse in current engineering education. The two courses taught at ICES are distinct in character in that they address social and group work issues at two different levels: a course on formulating engineering problems and a product design course that has industrial partners as clients. The first course is open only to engineering majors, while the second course is open to all students on campus. In the fall of 2000 we extended the first course to be a cross Atlantic joint course taught simultaneously at both TU Delft in the Netherlands and CMU. The primary goal of the problem formulation course has been to emphasize the importance of negotiations and tradeoffs among the stakeholders in the formulation of any design problem. Further, we emphasize the need for a precise articulation of the problem to serve as a contractual agreement among the stakeholders.

This second course has attracted students with majors from industrial design, technical writing, and human computer interaction, as well as students from all of the engineering disciplines. This course is a project course with the objectives of having students work together in a group with an industrial partner and of cultivating within the students a healthy respect for other disciplines and their high value in contributing to engineering design. An important aspect of both of these courses is we have the students learn by doing and from exemplars before we teach them the generalizations. This approach is usually much more interesting and is the reverse of much of the lecturing they see in many of their classes (Felder, 1993).

In the next sections we shall lay out the pedagogical objectives of these two courses and the experience we have gained in teaching them. In the concluding section, we contend that these two courses are complementary and are very important in creating a well-rounded multi-dimensional (social and technical) perspective on the role of engineering design in society.

Problem formulation in engineering design (Herder, Subrahmanian, Talukdar, Turk and Westerberg)

From 1989 to 1996, we taught this course as an engineering process and methods course as one of the EDRC design minor courses at CMU. We based the method of teaching on lectures and assignments and on a term project to formulate and solve a given design problem. During these years, we were uneasy about the way students approached problem formulation, which led us to understand that our students were good at solving well-structured problems but had difficulty in structuring and articulating new problems. To address this deficiency we radically changed the structure of the course 1997. In its new format, the primary objective of the course is to teach the process of problem formulation and the role of mathematical and other modeling techniques to aid in engineering design problem formulation. We do not ask the students to solve problems, only to formulate them. To this end, we have adopted a strategy by which we make the students focus on articulating the design problem by using a four-part description of design problems: (I) goals (as objectives and constraints), (II) tests, (III) design spaces and (IV) starting points. Here the pedagogical objective is to get the students to understand that articulating the right problem, based on a process of negotiation and clear representation of the problem among the stakeholders and the design team, is more important than being able to solve perfectly the wrong problem. It is our belief that rationality in design cannot be assigned just to the mathematical solution process. Articulating the right problem is an integral part of rationality and is a socially negotiated process (Bucciarelli, 1998, 2000)

This course attempts to raise awareness of this perspective. We ask students initially to formulate a number of small design problems – such as designing the best route from CMU to the airport. They do some of these problems individually to become familiar with the use of the basic framework of goals, tests, design spaces and starting points and with the use of mathematics as a language for articulating and unambiguously representing a problem. Once they are reasonably familiar with this way to recast problems, we then escalate to larger group-based assignments. At least one such project includes uncovering the formulation of an existing design project. The large assignments include design problems, such as design of a transportation system for Pittsburgh and the design of a water/sewage system for a new housing development near Amsterdam. Each week the students present their solutions to the class. Students thereby watch how other groups approach similar or even the same problems. The instructors serve as stakeholders for many of the problems. We introduce models of formulation from optimization (linear, non-linear, mixed integer), mathematical logic, game theory, information systems, organizational design and ethics through exemplars from real design problems.

Finally the student groups are asked to read and report both orally and as written reports on books from a list we provide in the area of engineering and design. They are not to meet face-to-face in preparing their reports, but rather they may only communicate electronically – e.g., by e-mail, phone, and chat. The books included have been on the design of the SR-71, of computers, and of the New York City water system; on the evolution of the design of air conditioners; and many of Petroski's books. The students were to analyze the design exemplars in the books and characterize them by using the four-part description we present to aid in formulating design problems.

International Experiment wit TU delft

Last fall CMU and TU-Delft conducted their first international experiment. We shared lectures through video exchange, and we organized the students as groups spanning both institutions. In order to make the transition to an internationally taught course as smooth as possible, the Dutch instructors attended parts of the course when it was taught at CMU in the Fall

of 1999. After concluding that this course would be very valuable also for Delft University (TUD) students, we set up an experiment for the Fall of 2000. This experiment comprised teaching (for instructors) and taking (for students) the course at the same time at the two different locations, with the use of as much as possible of each other's material and expertise. We spent a month of planning in the summer of 2000 to plan the course with respect to its contents and organization. Besides the technical issues that we had to solve, we had to overcome organizational intricacies such as timing and schedule differences. We do not discuss the latter in this paper, however.

The experiment we ran in teaching a course at the same time in two countries has been an educational one. We found that the use of video clips, in the way we used them in a classroom, has an added value. Students and instructors saw and presented different views on a subject, which improved understanding. We had expected the students to use the video clips as background material; they did not. The assigned problems had mixed settings in Europe and in the U.S., thereby suggesting the need for differences in preferences. Everyone in the class saw these very interesting differences arising as they articulated their problems.

The collaboration between the international groups was problematic in the beginning, as students had to become comfortable with the use of the various tools. With e-mailing, in particular, delay time caused by a six hour time difference remained a serious issue. Interactive collaboration tools, like chatting or telephoning, proved to be vital for some groups. The students used LIRE', a document management system developed at CMU within ICES. They captured and organized all their documents, presentations and reports on line for easy exchange and collaboration. A complete repository is available of the problems we have used in this course since 1996. Students could and did review previous problems to aid in solving their assignments. We have now captured all the video lectures from this last term as well.

We found that Delft faculty could use video lectures CMU faculty created, but, because of technical difficulties, the reverse proved very difficult. However, we learned that even students at Delft did not go back and look at the videotapes as they turned out to be too long. A postmortem of the course found that when they did use the videos, the students liked them as they as they could stop and discuss them while watching. This discussion woke them up, provided understanding of missed points, and so forth. To overcome the "too long" complaint, we plan to partition these tapes into short topical clips for use next fall. A report in the book entitled "Social Life of Information" (Brown and Duguid, 2000) inspired us to use video as medium around which to run the class. This report described how students in industry using video lectures from a university performed better than the students watching the live lecture. The report attributed this improved performance to the students' ability to interrupt and discuss lecture material as the lecture progressed. We feel this approach was useful, but it needs refinement based on the student suggestions. Herder et.al (2001) give more details on our experience in using video and other electronic technologies in this course.

In summary the purpose of the course is to create an understanding of how contexts and stakeholders determine the scope of the problem and how mathematical and other models can be used to articulate the problem. The emphasis here is on the role that models and methods play in the articulation and consensus building, rather than focusing only on how they allow one to solve the design problem. Student enthusiasm confirmed an added value to our collaborating across the Atlantic Ocean. They often mentioned that the experience could be like expected future real life situations. This collaborating with people with different perspectives at different times and places was, to them, the most valuable feature of the international part of the course.

Product design course (Subrahmanian, Westerberg, Garrett, Amon, Paredis, Jacobson)

In the past few years many of our students have been extremely interested in joining startup companies. They were of course dreaming of the excitement and of the potential early wealth. Four years ago, CMU and Lehigh University had Engineering Research Centers that were finishing their eleventh year and thus were graduating from having NSF funding. Our two universities approached the state of Pennsylvania to obtain alternative support for our respective centers, proposing to coordinate our efforts and direct them to local government and industry. One aspect we considered carefully was how to increase the retention of our engineering students within the state. We proposed creating a course that would connect local government and industry with our students, where the students would work on small design problems relevant to these organizations.

We endeavored to learn of courses taught elsewhere that might have a format we could emulate. We knew of a design project course at the University of Florida where students from throughout their engineering college participate for their entire senior year. Industry supplies both the problem descriptions and about \$15,000 of funding for each project. The university provides space and a faculty member who leads each project. About \$3000 of the funding becomes an unrestricted fund for use by this faculty member.

We also knew of entrepreneurial engineering courses at Stanford. We quickly became aware that many product design courses exist in many universities, including within CMU and Lehigh. These courses were typically within or closely tied to Mechanical Engineering Departments.

We elected to create an engineering design project course – but with a difference. The stated goals for our course were the following:

- increase retention of students within the Commonwealth of Pennsylvania,
- give students real problems on which to work,
- give them experience with the type of problem they could encounter in a startup,
- have the students learn how to improve the design processes in which they participate, and
- make the students much more aware of the many important non-technical aspects of design.

There are many aspects to engineering design our students typically will not see in a traditional capstone course. Student design teams are homogeneous – i.e., members are all one brand of engineer working on a problem type familiar to them. If someone leaves, someone else on the team can likely fill in quite easily. They typically do not experience project hand-off from one team to another. The design problems often have a well-defined objective – e.g., make 15% return on investment. They seldom think retrospectively about the design process itself.

To make this experience more interesting to the students and motivated by the goals stated above, we now have the following guidelines for our course. We have evolved these over time. The course is for four semester credits.

- Any junior, senior or graduate student on campus can participate. Indeed we actively solicit students from all colleges. And we deliberately create teams with very diverse membership. We had industrial designers and graduate electrical engineers working on a laser tape. The EE students remarked that the product would certainly have been a failure even with the best

analogue circuit if it had not been properly packaged and had the right intuitive buttons to push. English majors are not there just to write reports either. They take lead roles in organizing lectures, establishing protocols to discover stakeholder needs, and so forth. On a oil cleanup product, the non-chemists and chemical engineers looked at packaging, environmental impact, delivery and so forth.

- Each project can last as long as needed, with one year being a guideline. We started off believing each would be one year, but that was an artificial constraint for this course. We removed it. New projects start in any term, as needed and as available.
- Each project has a government or industrial partner who provides the initial problem definition (e.g., to design a device to teach young asthma patients how to control their asthma), technical support, and \$15,000 funding per year. The state funding we get allows us to cost share this funding under special circumstances.
- Students can take the course for one or two terms. Either option will be beneficial. Most do take it for one term only.
- We capture all paperwork electronically for the course. We want students to be able to access and use the available information, including that available for the other projects. This capture is also part of solving the handoff problem between terms when new teams pick up an existing project. Finally, we want a history from which we may all benefit in the future.
- There is one ninety minute class meeting each week. It is a non-threatening time of sharing.
- All students continually learn about all ongoing projects, and they help each other. There are to be NO secrets. Each project emphasizes only some of the interesting aspects of design, so, by observing closely all projects and to some extent being “sounding boards” for all projects, students gain a better appreciation of more of the issues.
- Students learn from each other – a guideline that is closely related to the previous one.
- We want students to understand the need for any of the methods we introduce and have the option to use and/or modify them as they wish. There are no “sacred” methods.
- The design is of a product. This decision is very deliberate. We suggest that products offer a very interesting experience. Products may be crudely defined as packaging highly technical things in a way that others can use them. It would be scary indeed if we had to understand the technology in all the things we need and use. The real world is all about products. The features products provide often define their success as much or more than the technologies within them. They tend to have short lives in the market place, always being displaced quickly by something with better features.

We started slowly. In our first term, Fall, 1998, we had only one project: the design of a distributed agent traffic control system with Bosch being the industrial partner. This experiment encouraged us to develop the larger course, which we have now taught five semesters in a row. It now typically has five projects each term and about 25 to 30 students.

From the time of the first course, students and faculty have stored all documents in the web accessible document management system, LIRE' (Living REpository) [Davis, Subrahmanian, et.al., 2000], which our *n*-dim research group created while working with an industrial partner. With the feedback we get, we continually improve this system, and today it is really a very nice system. Among LIRE' features are access control, notification when things are added or changed, arbitrary linking of documents, searching, and the automatic converting of all documents to a viewable form (generally a pdf).

We instituted having the students give five minute progress reports every week very early in this course. Progress reporting is a great way to assure progress every week. Students do not like being embarrassed with reports that admit to doing little or nothing the week before.

A feature we instituted in the spring of 2000 was to have the students prepare and present the lectures on the methods that the text [Dym and Little, 19xx] presents as being useful for student sized product design projects. It could appear we are being lazy. However, this is every bit as much work for us. Our rationale is that we have had a lot of experience teaching. They will have to lecture a lot when they are in their future jobs. Perhaps we can impart some ideas on how to create interesting lectures to them. We have issued guidelines telling the students how we think they should prepare a lecture.

The most important guideline we give to them is to teach by example first, then generalize. Each week one group prepares its notes and then meets on Thursday with us for about an hour. We discuss their lecture in detail. They almost always prepare their lecture by presenting the method in general terms and then applying it. Basically they prepare a pretty dry lecture. We discuss with them the advantages of applying it and then generalizing it. We show them how they can engage the students. On Monday they return with their next version. This one hour discussion leads to the version they teach on Tuesday. Their lecture lasts 30 minutes. As faculty we do not save time this way. It takes us as long or longer to teach them how to prepare the lecture as it would for us to do it ourselves. But, amazingly, they always prepare great lectures, better than we would have. The students actually clap after the first such lecture every term (and then by courtesy after all the others for the rest of the term). Each group creates two lectures each term. In the first they use PowerPoint slides, but in the second they can only use the blackboard. The second makes them much more nervous. We have to control them to stop them from having one person fill a board while a second erases it or while a second starts to write “ahead” of the lecture. We try very hard to get them to put up just enough for good notes. We tell them that lectures are not to be “core dumps” of vast amount of material. All in all it is fun for everyone. And we ask them to look at the lectures they now sit in and assess why they do or do not work well.

Once the lecture is completed, the students then work for about 20 minutes with the other groups to apply the method they just taught to the other projects. At first this application was for one project with the whole class watching. This term, however, each member of the lecturing team has gone to a separate group and been the expert. The students get to learn another lesson with this activity: just how hard it is to get started when applying a method. For example, the list of product features does not magically appear as it seems to do in the lecture.

We do NOT grade the lecturing nor the project summaries. Peer pressure really assures us these are done well.

We like to think that this type of course may be a far better capstone course for our students that the domain specific design courses they now take in engineering. The domain specific course should still exist as it is often where we teach students those tools that our disciplines have available to aid in design. For example, we teach students about simulators, about synthesis insights, and so forth related to chemical process design in chemical engineering.

But product design where we involve all students on campus requires a broader use of all that students learn in their university experience. Shouldn't that be a better capstone course? (Yes, we know; where will we find room for it in our curriculums?)

Conclusions

The interaction of the social and the technical in engineering design is undisputable. While engineering curricula have concentrated much on the science of engineering, social and work aspects have been generally put in the back burner. Recently several universities and institutions such as Harvey Mudd, Stanford, the University of Florida and others have introduced different models for the introduction of courses to address this deficiency. We at CMU have borrowed ideas from others and have refined the course over several years to address various pedagogical issues that we found wanting in the current curricula. However, the three primary principles that have guided the development these courses are a) learning by doing, b) teaching from exemplars to generalizations and c) learning from each other and respecting each others skills and perspectives. Both courses typically have 20 to 30 students. Students like the courses. They understand that they are participating in an educational experiment. Students often give us suggestions on how to improve their educational experience, and many of these are now part of the courses. The two courses are complementary as they require skills at different levels of social interaction and group dynamics in the different phases of design.

We believe that the problem formulation course, with its framework of goals, tests, design spaces and starting points, provides a critical way of not only articulating new design contexts but also of analyzing existing designs to uncover their underlying assumptions and goals. The second course emphasizes communications, reconciliation, use of methods for systematic translations from user needs to product definitions and implementation. Many of our students from the first course take the second and vice versa – a casual empirical observation on the student interest in these course. We intend to continue learn from experiences of others and ours along with maintaining an openness for suggestions from the students and our industrial partners to make it a rich educational experience that sets the students up for a lifetime of learning.

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Old material to be chopped off or used – for reference only

We started the product design course as a small experiment with Robert Bosch Corporation. We ran a student project that was relevant to their interest and where personnel from Bosch could participate. This small experiment led us to create a two-semester course open to all juniors, seniors and graduate students at CMU. While projects generally last two semesters, students are not required to take both semesters – thus exposing them to the “hand-over” problem. Also, industry sponsors all projects; we typically assign an industrial participant and a faculty advisor to run each group. While many such product design courses exist in several places, the pedagogical strategy we have taken in this course is quite different from courses we have seen elsewhere. The three main pedagogical objectives in this course are to improve: a) the ability to choose and apply methods and communicate the methods used to others using different communication media, b) the ability to maintain design history and record that is transferable to the next semester’s group and, c) the ability to learn from each other in groups of multidisciplinary teams.

In order to teach the students the methods they would need to use in the design process, the students have to be introduced to the methods. We have adopted the design text by Dym and Little, but instead of providing a set of “dry” lectures, we have the students groups prepare and present the lectures. We coach them on how to create each lecture. Rather than presenting the methods as procedures, they illustrate the methods on their problem followed by an interactive session where they choose a group (at random) and with that group start to apply the method to that group’s problem. In one round of the lectures they use PowerPoint slides to teach; in the second round they can only use the blackboard. The primary goal of these exercises is to teach them how to present material first from examples and then by indicating the generalizations. This approach is usually much more interesting and is the reverse of much of the lecturing they see in many of their classes¹.

The other aspect of this course is that students capture and exchange all the history of a project during the semester and across semesters through a collaborative document management systems called LIRE’. This course provides a real world environment where groups start projects that others take over. The third aspect of the course is that the students are working on problems that range from software engineering to other hard engineering disciplines. Examples include design of a material to clean up oils spills, a web based system to teach air separation to high school and undergraduate students, circuit breaker design, deicing “People Mover” guide ways, and design of a laser measuring tape system. Through the class presentations, students get to see the different projects throughout their different phases.

In summary we feel that these two courses address different aspects of the social aspects of design - the first course in the arena of problem formulation and second in the area of design practice. Both courses enhance the student experience by letting them share their formulation and solution processes and thereby providing a continuous social learning process and awareness of social contexts. This

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¹ Felder, Richard, "Reaching the Second Tier: Learning and Teaching Styles in College Science Education." *J. College Science Teaching*, 23(5), 286-290 (1993).